



TITLE:

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CITATION:

Nunokawa, Mamoru ...[et al]. Univalence of analytic functions associated with Schwarzian derivative (Conditions for Univalence of Functions and Applications). 数理解析研究所講究録 2011, 1772: 104-108

ISSUE DATE:

2011-12

URL:

<http://hdl.handle.net/2433/171684>

RIGHT:

Univalence of analytic functions associated with Schwarzian derivative

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The authors would like to dedicate this paper to the late Professor Shigeo Ozaki

1 Introduction

Let \mathcal{A} denote the class of functions $f(z)$ of the form

$$(1.1) \quad f(z) = z + \sum_{n=2}^{\infty} a_n z^n$$

which are analytic in the open unit disk $\mathbb{U} = \{z \in \mathbb{C} : |z| < 1\}$. For $f(z) \in \mathcal{A}$, the following differential operator

$$(1.2) \quad \begin{aligned} \{f(z), z\} &= \left(\frac{f''(z)}{f'(z)} \right)' - \frac{1}{2} \left(\frac{f''(z)}{f'(z)} \right)^2 \\ &= \frac{f'''(z)}{f'(z)} - \frac{3}{2} \left(\frac{f''(z)}{f'(z)} \right)^2 \end{aligned}$$

is said to be the Schwarzian derivative of $f(z)$ or the Schwarzian differential operator of $f(z)$. For the Schwarzian derivative of $f(z) \in \mathcal{A}$, the following results by Nehari [2] are well-known.

Theorem A *If $f(z) \in \mathcal{A}$ is univalent in \mathbb{U} , then*

$$(1.3) \quad |\{f(z), z\}| \leq \frac{6}{(1-|z|^2)^2} \quad (z \in \mathbb{U}).$$

The equality is attained by Koebe function $f(z)$ given by

$$(1.4) \quad f(z) = \frac{z}{(1-z)^2}$$

and its rotation.

Theorem B *If $f(z) \in \mathcal{A}$ satisfies*

2010 *Mathematics Subject Classification*: Primary 30C45

Key Words and Phrases: Analytic function, Univalent function, Schwarzian derivative

$$(1.5) \quad |\{f(z), z\}| \leq \frac{2}{(1-|z|^2)^2} \quad (z \in \mathbb{U}),$$

then $f(z)$ is univalent in \mathbb{U} .

For Theorem B, Hille [1] has noticed that 2 in (1.5) is the best possible constant.

Let us define the function $g(z)$ by

$$(1.6) \quad g(z) = \frac{f'(x)(1-|x|^2)}{f\left(\frac{z+x}{1+\bar{x}z}\right) - f(x)}$$

$$= \frac{1}{z} + \bar{x} - \frac{1}{2}(1-|x|^2)\frac{f''(x)}{f'(x)} - \frac{1}{6}(1-|x|^2)^2 \left\{ \left(\frac{f''(x)}{f'(x)}\right)' - \frac{1}{2} \left(\frac{f''(x)}{f'(x)}\right)^2 \right\} z + \dots$$

$$= \frac{1}{z} + h(z, x)$$

for $f(z) \in \mathcal{A}$ and some complex x such that $|x| < 1$, where

$$(1.7) \quad h(z, x) = \bar{x} - \frac{1}{2}(1-|x|^2)\frac{f''(x)}{f'(x)} - \frac{1}{6}(1-|x|^2)^2 \left\{ \left(\frac{f''(x)}{f'(x)}\right)' - \frac{1}{2} \left(\frac{f''(x)}{f'(x)}\right)^2 \right\} z + \dots$$

Then, it is easy to see that $g(z)$ is univalent in \mathbb{U} if and only if $f(z)$ is univalent in \mathbb{U} .

On the other hand, Ozaki and Nunokawa [3] have given the following result.

Theorem C *If $f(z) \in \mathcal{A}$ is univalent in \mathbb{U} , then*

$$(1.8) \quad |h'(0, x)| \leq \frac{(1-|x|^2)^2}{6} |\{f(x), x\}| \leq 1 \quad (|x| < 1).$$

If $f(z) \in \mathcal{A}$ satisfies

$$(1.9) \quad |h'(0, x)| \leq \frac{1}{3} \quad (|x| < 1),$$

then $f(z)$ is univalent in \mathbb{U} .

To discuss the univalence for our problem, we have to recall here the following result which is called Darboux theorem.

Lemma 1 *Let \mathbb{E} be a domain covered by Jordan curve C and let $w = f(z)$ be analytic in \mathbb{E} . If a point z moves on C in the positive direction, then w also moves on the Jordan curve $\Gamma = f(C)$ in the positive direction. Let Δ be the inside of the curve Γ . Then $w = f(z)$ is univalent in \mathbb{E} and maps \mathbb{E} onto Δ conformally.*

Proof Let $w_0 \in \Delta$ and $\phi(z) = w - w_0 = f(z) - w_0$. Then $\phi(z)$ is analytic in \mathbb{E} , $\phi(z) \neq 0$ on C , and

$$(1.10) \quad \frac{1}{2\pi} \int_C d \arg \phi(z) = \frac{1}{2} \int_\Gamma d \arg(w - w_0).$$

From the argument theorem, the left hand side of (1.10) shows that the number of zeros of $\phi(z)$ in \mathbb{E} and the right hand side of (1.10) shows the argument momentum when w moves on Γ in the positive direction. Therefore, the right hand side of (1.10) should be just one. This shows us that $\phi(z) = f(z) - w_0$ has one zero in \mathbb{E} .

Let us put $w_0 = f(z_0)$. Then there exists only one point $z_0 \in \mathbb{E}$ for an arbitrary $w_0 \in \Delta$. This means that $f(z)$ is univalent in \mathbb{E} .

For the case of $w_0 \notin \Delta$, we obtain that

$$(1.11) \quad \int_C d \arg(w - w_0) = 0,$$

which gives us that $\phi(z) = f(z) - w_0$ has no zero in \mathbb{E} . This completes the proof of the lemma.

We note that we owe the proof of Lemma 1 by Tsuji [4].

2 Univalence of functions associated with Schwarzian derivative

An application for Lemma 1 derives

Theorem 1 *If $f(z) \in \mathcal{A}$ satisfies*

$$(2.1) \quad \operatorname{Re} h'(z, x) > \alpha \quad (z \in \mathbb{U})$$

for some real α ($\alpha > 1$) and for all $|x| < 1$, then $f(z)$ is univalent in \mathbb{U} , where $h(z, x)$ is given by (1.7).

Proof Let us put $0 < |z| < 1$ and $|x| < 1$. Then, using $g(z)$ and $h(z, x)$ given by (1.7), we have that

$$(2.2) \quad g(z) - \frac{1}{z} = h(z, x)$$

is analytic in \mathbb{U} . Note that $f(z)$ is univalent in \mathbb{U} if and only if $g(z)$ is univalent in \mathbb{U} . We know that

$$(2.3) \quad \left(g(z_2) - \frac{1}{z_2} \right) - \left(g(z_1) - \frac{1}{z_1} \right) = h(z_2, x) - h(z_1, x) = \int_{z_1}^{z_2} \left(\frac{dh(z, x)}{dz} \right) dz,$$

where the integral is taken on the line segment $z_1 z_2$ such that $z_1 \neq z_2$ and $0 < |z_1| = |z_2| = r < 1$. Letting

$$z = z_1 + (z_2 - z_1)t \quad (0 \leq t \leq 1),$$

we have that

$$(2.4) \quad \int_{z_1}^{z_2} \left(\frac{dh(z, x)}{dz} \right) dz = (z_2 - z_1) \int_0^1 \left(\frac{dh(z, x)}{dz} \right) dz.$$

Therefore, we obtain that

$$g(z_2) - g(z_1) + \frac{z_2 - z_1}{z_1 z_2} = (z_2 - z_1) \int_0^1 h'(z, x) dt.$$

This gives us that

$$(2.5) \quad \begin{aligned} \frac{g(z_2) - g(z_1)}{z_2 - z_1} &= \int_0^1 h'(z, x) dt - \frac{1}{z_1 z_2} \\ &= \int_0^1 \left(h'(z, x) - \frac{1}{z_1 z_2} \right) dt. \end{aligned}$$

If there exist two points z_1 and z_2 such that $z_1 \neq z_2$ and $|z_1| = |z_2| = r < 1$ for which $g(z_1) = g(z_2)$, then we have that

$$0 = \int_0^1 \operatorname{Re} \left(h'(z, x) - \frac{1}{z_1 z_2} \right) dt > \int_0^1 \left(\alpha - \frac{1}{|z_1 z_2|} \right) dt = \frac{\alpha r^2 - 1}{r^2}.$$

Therefore, letting $r \rightarrow 1^-$, we see that

$$\int_0^1 \operatorname{Re} \left(h'(z, x) - \frac{1}{z_1 z_2} \right) dt > 0.$$

This is the contradiction and shows that there exist no points z_1 and z_2 such that $z_1 \neq z_2$ and $g(z_1) = g(z_2)$ in \mathbb{U} . Since $g(z)$ is univalent in \mathbb{U} , using Lemma 1, we conclude that $f(z)$ is univalent in \mathbb{U} .

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